# Review of an ADAS Report 'The Agronomic Case for Polyhalite', dated 8 April 2014

This review was written by Mr A. E. Johnston, Lawes Trust Senior Fellow, Rothamsted Research, Harpenden at the request of the North York Moors National Park Authority. My review also includes an Appendix to present in more detail terminology and methodology used in experiments testing fertilizers. In addition, for the reasons given on page 16 of this review, there is now an Addendum which presents in detail the results of the experiments commissioned by Sirius Minerals and a discussion of the findings.

## 1. Introduction

As part of their submission for extracting polyhalite from underground deposits using access from works in the North York Moors National Park, York Potash have submitted a report, namely the Agronomic Case for Polyhalite by ADAS, 8 April 2014 (The ADAS Report), commissioned by Sirius Minerals PLC. The reason advanced for mining the polyhalite deposits is to sell it as a fertilizer because it contains four plant nutrients required by crops that are grown for use as food, feed, fibre or biofuels. I have been asked by the North York Moors National Park to review this Report for use of polyhalite as a fertilizer. Additionally, I was given access to the "Data Room" to check whether my interpretation of the data from the pot and field experiments commissioned by Sirius Minerals agrees with that in the ADAS Report.

I, Mr A. E. Johnston am an agricultural research scientist specialising in soil fertility and crop nutrition. In March 1953 I joined the Chemistry Department at Rothamsted Experimental Station (now Rothamsted Research) and since then have worked on many aspects of soil fertility and crop nutrition. On retiring as Head, Soils and Crop Nutrition Division in 1989 at the then compulsory retirement age of 60, the Lawes Agricultural Trust honoured me with a Senior Fellowship which has allowed me to use the facilities at Rothamsted to continue with my scientific interests. I have continued to write scientific papers, reviews, reports and articles for farmers and their advisors and now have some 300 publications. In recognition of these various contributions to agricultural science I have been the recipient of the Annual Crop Nutrition Award of the International Fertilizer Industry Association in 1994, the Francis New Memorial Medal of the International Fertiliser Society in 1997, an invitation to give the prestigious Leo M Walsh Memorial Lecture at the Annual Meeting of the American Society of Agronomy in Long Beach, California in 2010 and the Science Award of the International Plant Nutrition Institute in 2013.

Before reviewing the ADAS Report, Section 2 of this report gives some general points about soil fertility, crop nutrition and the principles of fertilizer use to better understand my comments on the Report submitted by York Potash.

## 2. Soil fertility, crop nutrition and fertilizer use

This Section contains a few facts about soil fertility and crop nutrition with, where given, examples related to potassium, calcium, magnesium and sulphur because these are the four nutrients in polyhalite.

**2.1. Conventions adopted** In this report potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) will be used when referring to the element as a plant nutrient in crops. To determine the amount of each of these four elements taken up by/or removed by a crop in harvested produce, the percent in dry matter is multiplied by the dry matter yield. In commercial practice potassium is frequently referred to as potash, taken to mean $K_2O$ (the oxide of potassium) and it is in this form, together with the oxides of calcium, magnesium and sulphur, i.e. as $K_2O$, CaO, MgO and $SO_{3,}$ that the concentration in these four elements in fertilizers must be declared. Sometimes, as in the Fertiliser Manual RB209, the concentration of potassium in a crop is given as $K_2O$ to aid the calculation of how much potassium to apply in fertilizer. this is done in the Tables of potassium in crops.

### 2.2. Soil fertility, crop nutrient requirement and choice of fertilizer

Plant roots take up these four nutrients from the soil solution (the water in the soil) in the ionic form, i.e. as $K^+$, $Ca^{2+}$, $Mg^{2+}$ and $SO_4^{2-}$, and the amount of each nutrient in the soil solution is usually very small. However, potassium, calcium and magnesium frequently occur in soil minerals and together with sulphur in soil organic matter. From these sources the nutrients become available in the soil solution in varying amounts, from soil minerals by weathering and by microbial breakdown of soil organic matter. In addition, considerable amounts of $K^+$, $Ca^{2+}$ and $Mg^{2+}$ are held in many soils by the negative charge on the surface of many clay minerals and soil organic matter, and when held in this way these three nutrients are a readily plant-available reserve. As the concentration of each ion in the soil solution is lowered by uptake by roots it is replenished from this reserve. Thus, the sole role of a fertilizer is to supplement the supply of readily-available plant nutrients in soil when there is too little to achieve optimum economic yields. Consequently, farmers will assess by soil analysis the nutrient status of the soil in each field and purchase a fertilizer to make good any deficiency. I cannot see any farmer buying a fertilizer containing nutrients that are not needed to supplement the supply that already exists in the soils on the farm, especially in the current economic climate.

### 2.3. Soil analysis and fertilizer recommendations

This topic is discussed in more detail in Appendix A2 of this report, including the use of the fertilizer recommendations in the DEFRA Publication RB209, which is applicable to England, Wales and Northern Ireland, but not to Scotland. RB209 takes different approaches to recommendations for the four nutrients in polyhalite based on decisions as to whether it is necessary to supplement the existing plant-available supply in the soil. Plant-available potassium and magnesium can be retained in soil and any recommendation for their application is based on analysis of a representative soil sample from each field taken every 3 to 5 years. The aim is to first raise and then maintain a certain level of plant-available potassium and magnesium. This is given as K Index 2- for arable crops and grass, and K Index 2+ for vegetables; and for magnesium not above Mg Index 1. There is no specific recommendation for calcium because maintaining soils above pH 6.0 by applying chalk or lime when required will maintain a sufficient supply of plant-available calcium. The approach for sulphur is different. Sulphur as the sulphate ion is taken up by roots but the sulphate ion is not retained in soil and in consequence sulphur must be applied each year. In the past aerial deposition of sulphur has supplied sufficient for crop needs but diminishing amounts of sulphur from the atmosphere now means that it may be necessary to apply sulphur to supplement the soil supply. From a map of sulphur deposition in England, Wales Scotland and Northern Ireland in RB209 farmers can see if they are in an area where sulphur deficiency is likely and decide whether to apply sulphur to crops sensitive to sulphur deficiency.

### 2.4. Crop nutrient requirement, crop nutrient content and polyhalite

In the literature and presentations by York Potash the phrases “balanced fertilisation” and “balanced supply” are used frequently, and often incorrectly, see Appendix A5. Polyhalite is not a balanced fertilizer because it does not contain other nutrients required by crops, especially nitrogen and phosphorus. Equally polyhalite does not contain a balanced supply of the four nutrients. The ratio of potassium to calcium to magnesium to sulphur in polyhalite is very different to the ratio of the concentration of these four elements in a growing plant, see Table 5 in Appendix A5.2 for examples. The ratio in polyhalite compared to that in crops shows that polyhalite contains too much sulphur and calcium and too little potassium. Consequently, if polyhalite is used as the sole source of potassium the amount of polyhalite required to supply this amount of potassium adds far too much sulphur and calcium and only about the right amount of magnesium, see Table B in Appendix A5.2.

## 3. Comments on the Executive Summary to the ADAS Report

The chemical formula for the naturally-occurring mineral polyhalite is given as $K_2Ca_2Mg(SO_4)_4.2H_2O$, i.e. polyhalite contains four plant nutrients, potassium, calcium and magnesium, all three as their sulphate salts so that polyhalite also contains sulphur. Although these four plant nutrients are essential for plant growth, crops vary in the amounts of each they require to achieve optimum growth. The ADAS Report notes that for fertilizers the content of these four nutrients have to declared as their oxides, namely 14% $K_2O$, 48% $SO_3$, 6% MgO and 17% CaO. Thus, sulphur is by far the largest component and perhaps not to emphasise this fact Sirius Minerals sometimes and incorrectly give the sulphur content as 19% S. On the basis of the chemical analysis of polyhalite, the authors of the ADAS Report note that “*Potassium and sulphur are the most valuable nutrients in Polyhalite*”. But it is not clear what is meant by *valuable*, economic value which means it must be compared with other sources of these nutrients, or simply that of the four nutrients most crops require more potassium and sulphur than magnesium and calcium.

Predictions for the increasing demand for potassium and sulphur in crop production are given by many different organisations but they are only predictions and the authors of this ADAS Report are not able to say what proportion of this demand may be met by polyhalite. There are so many other materials containing these four elements currently available on the world market. They include for potassium, muriate of potash (MOP) and sulphate of potash (SOP), which also contains sulphur. Sulphur is readily-available as gypsum/phosphogypsum and magnesium as kieserite/calcined magnesite or magnesian limestone and calcium as chalk and limestone. Compared to these other readily-available materials, I consider it would be necessary to identify some unique properties in polyhalite in relation to the supply of these nutrients to justify a considerable increase in its use as a fertilizer in addition to the small amounts already available and used.

The Executive Summary does not contain the following comment on the pot and field-scale experiments that is found in Section 4 of the ADAS Report. The comment about the experiments is that they were *"…designed to rigorously evaluate the effects of polyhalite….",* yet later in Section 4 (page 24) there is an important note, not repeated in the Executive Summary, namely *"some caution should be taken in interpreting these results* (of the pot and field experiments) *because although the potash content of the fertilizer applications (i.e. those tested in these experiments) was usually equilivent for each fertilizer added, the fertilizers almost always differed in the content of other nutrients (*required by plants for optimum growth*) including sulphur, magnesium and calcium and these were not accounted for or balanced in any of the studies reported. Therefore, the differences observed may not necessarily be the result of greater potash availability for plants, but instead may be related to the availability of one or more of the other nutrients."* The omission of this note from the Executive Summary is I consider important because the York Potash case for mining polyhalite in the NYM NP is its importance as a fertilizer and yet no conclusive evidence for any unique property has been shown in the experiments commissioned by Sirius Minerals.

Comment is also made that "polyhalite has a *potential* (my italics) advantage over muriate of potash (MOP, potassium chloride) when used on crops that are sensitive to chloride." Yet MOP has been used in increasingly large amounts during the last 150 years suggesting that "chloride sensitivity" while it exists in some crops, especially under certain conditions, including drought, is not a serious issue for many growers. Where there is a problem with applications of chloride, potassium sulphate (SOP) is readily available.

The Executive Summary also notes that, " …polyhalite significantly increases growth of a wide range of crop species… ", but with great care the authors do not say here what the comparison was with and what was the level of significance. The results of the pot and field-scale experiments will be discussed in detail in Section 5 of this report.

The authors with commendable diligence have made estimates of the amounts of potassium, sulphur and magnesium removed by the major global crop species and for 16 of these crops they calculate that the annual amount of these three nutrients are 37.8 Mt of potash as $K_2O$, 13.3 Mt of sulphur as $SO_3$ and 13.3 Mt of magnesium as MgO. The authors are, however, careful to note that these crops "**will therefore potentially benefit from polyhalite fertilizer addition in situations where the soil supply of these nutrients is limiting.** As discussed in Section 2 and the Appendix of this report, the cost effective use of fertilizers requires that they are only applied to supplement the plant-available supply of each nutrient already in the soil. Rightly in my opinion the authors of the ADAS Report do not make any attempt to indicate what proportion of the world's soils are likely to be deficient in all three nutrients at the same time, never mind the proportion of any one of the three nutrients individually. I consider that the proportion of soils likely to be deficient in all three nutrients will be very small, which suggests that the global market for polyhalite to supply all three nutrients to correct a deficiency in the soil will be very small. Additionally the ratio of the three nutrients in polyhalite is such that applying sufficient polyhalite to meet the need of one nutrient invariably means that too much or too little of one of the other nutrients in polyhalite are added, see Table C in Appendix A.7.2. There could be a number of soils deficient in just one of these nutrients and this deficiency could be corrected by applying one of the many appropriate single nutrient fertilizers. I can't conceive that farmers would purchase a multi-nutrient fertilizer like polyhalite to correct deficiency of one of the nutrients it contains.

The final paragraph to the Executive Summary of the Agronomic Case for Polyhalite by ADAS (page ii) simply notes, "*In summary, Polyhalite is a valuable source of major plant available nutrients (i.e. potash, sulphur and magnesium) that can be used to produce multi-nutrient fertiliser products or as a straight product. ….*" I do not consider this statement to be a very strong endorsement for the use of polyhalite because the Report does not demonstrate that polyhalite has any unique properties and the plant nutrients in polyhalite are readily available world-wide in other materials; potassium as potassium chloride (muriate of potash, MOP), sulphur as gypsum/phosphogypsum, magnesium as kieserite/calcined magnesite or magnesian limestone and calcium as chalk and limestone.

## 4. Comments on Section 3 of the ADAS Report - Function and supply of potassium, sulphur, magnesium and calcium.

I have sympathy with the authors of the ADAS Report in that much of this Section of their Report has had to be illustrated using examples from British agriculture while it appears elsewhere that Sirius Minerals intend to sell polyhalite globally. Other than in very general terms the extrapolation of information applicable to British agriculture to the global scale is fraught with difficulties. This is especially so when general observations about fertilizer use on British crops are used to support what the global demand might be for polyhalite and for each of the crop nutrients contained in polyhalite. Thus, although factual data are taken from well-recognised sources and can be shown to be correct, inferences drawn from British agriculture should be taken with caution, perhaps disregarded, and not used to imply what may be needed on a global scale. In the following discussion the section numbers are those in the ADAS Report.

Section 3.1. Potassium

3.1.1. *Plant requirement*. Well-accepted facts

3.1.2. *Supply (of potassium) from soil*. The soil supply of plant-available potassium is very difficult to predict and yet the need to apply a potash fertilizer and the amount to use depends on how much comes from the soil each year, as discussed in more detail in Section 2 of this report and the Appendix. Determining the soil supply requires data from long-term experiments on different soil types, and globally there is very little appropriate data. Thus, while the information in the ADAS Report for UK soils is interesting it cannot be used to assess the global need for potash fertilizers let alone polyhalite which supplies three major nutrients two of which may not be required on many soils.

3.1.3. *Potash fertilizer production and consumption*. Statistics used here are taken from acknowledged sources. If the four principle users of potash fertilizers are China (26%), Brazil (16%), USA (14%) and India (8%), and there is little requirement for polyhalite in the UK domestic market much of the output from a new nine proposed by York Potash will be exported with an associated environmental cost.

3.1.4. *Potash use by crops*. Table 3 gives the application of potash to the world's crops as 27.4Mt $K_2O$ while Table 2 gives total potash consumption as 30.36Mt $K_2O$. Both quantities are estimates, which will have some error, but the amounts suggest that currently more potash is being supplied than is required by crops, and consequently the inference would be that new sources of potash are not required.

3.1.5. *Potash supply from application of organic manures*. Tables 4, 5 and 6 are very interesting and include potassium inputs not only from organic manures but also from fertilizers and other sources. The data are only applicable to the UK and it is impossible to predict world use from them and thus possible demand for a new source of potash fertilizer.

There are many potash fertilizers that contain more potassium than polyhalite, for example, potassium chloride, muriate of potash (MOP) 60% $K_2O$, sulphate of potash (SOP) 50% $K_2O$ and potassium nitrate ($KNO_3$) 45% $K_2O$.

Section 3.2 Sulphur

3.2.1. *Plant requirement.* Accepted facts

3.2.2. *Supply from the soil.* The sulphate ion ($SO_4^{2-}$) is the form in which sulphur is taken up by plant roots but in most soils there is no mechanism that will retain sulphur in this ionic form so sulphate is readily leached from soil in drainage water. This is the opposite to what happens with potassium, calcium and magnesium, all three elements as positively charged cations are retained in soil, see details in Section 2 and the Appendix. The only soil supply of sulphur comes from the mineralisation (microbial breakdown) of soil organic matter.

3.2.3. *Supply from atmospheric deposition.* The ADAS report is correct in that the sulphate ion, dissolved in rainwater, and sulphur dioxide in dry deposition have been the principle sources of the sulphur required by plants grown in many soils worldwide, and the amount of sulphur added to soils from these sources has been declining appreciably.

3.2.4. *Sulphur fertilizer and consumption.* The ADAS Report notes that, due to the global decline in sulphur inputs to soil by atmospheric pollutants, there has been an estimate of a worldwide sulphur deficit in agriculture of about 11Mt $SO_3$ in 2014, and about half this estimated deficit is said to be in China and India. However, sulphur as sulphate occurs naturally in large deposits of gypsum, used to make plaster board among other things, and is also becoming available as phosphogypsum a co-product of the wet-acid process for making phosphoric acid used mainly in phosphate fertilizers. Currently, large amounts of phosphogypsum are used in agriculture and this is a primary source of sulphate in many parts of India.

3.2.5. *Sulphur use in UK.* Detailed discussion of what has happened in UK is interesting but hardly applicable to a world scenario. I can agree with part of the general conclusion (page 13) that there will be increasing need for sulphur fertilizers globally but I'm not convinced that polyhalite has a major contribution to make when so many other sources of sulphur are available. For example, the sulphur content of polyhalite (48% $SO_3$) is matched by the sulphur content of other fertilizers, ammonium sulphate, 60% $SO_3$, which also contains 21% N; potassium sulphate (SOP) 45% $SO_3$, which also contains 50% $K_2O$. This implies that polyhalite has no unique properties in the supply of the three nutrients it contains. The availability of sulphate in gypsum, 40% $SO_3$ and 32% CaO, and phosphogypsum see above are other important sources of sulphate.

3.3. Magnesium

3.3.1. *Plant requirement* Accepted facts

3.3.2. *Supply from the soil.* The indigenous soil supply comes from the weathering of naturally occurring minerals in soil and is therefore very soil specific. As for potassium, long-term experiments for every major soil type would be required to assess the rate and longevity of the release of sufficient amounts of magnesium to satisfy crop requirement. Thus, it is not possible to say with any degree of certainty when the need to supply magnesium might become important. For example, the ADAS Report notes that less than 13% of UK soils are thought to have less than the desired amount of plant-available magnesium to achieve optimum yield. Even to guess how much magnesium fertilizer that might be required globally is impossible.

3.3.3. *Commonly available fertilizers that supply magnesium.* Polyhalite contains only 6% MgO, which is about the same as the magnesium content of kainite (5% MgO but kainite also supplies potassium (11%$K_2O$) and sulphur (10% $SO_3$). Both kieserite, 25% MgO and 50% $SO_{3,}$ and magnesium sulphate 16% MgO and 33% $SO_3$ supply more magnesium than polyhalite and some sulphur as well. Again illustrative of the fact that polyhalite has no unique properties and the nutrients it contains are readily available in other fertilizers.

3.4. Calcium

The ADAS Report says little about calcium because to achieve optimum, economic yields of most crops requires that soil acidity should not be less than pH 6.0 measured in an aqueous suspension. Soils at pH 6.0 and above will contain more than enough calcium to meet crop requirement. If calcium is required fertilizers like calcium nitrate, 29% CaO, and single superphosphate 35% CaO contain more calcium than polyhalite 17% CaO. On acid soils, Gafsa rock phosphate, 32% CaO, is a useful source of calcium.

## 5. Comments on Section 4 of the ADAS Report - Review of existing published and unpublished information on the effects of Polyhalite on plant growth

**5.1.** York Potash is seeking permission to mine polyhalite to sell as a fertilizer because it contains potassium, calcium, magnesium and sulphur, four of the nutrients required by plants. To demonstrate that any material offered for sale is a source of one or more plant nutrients requires experiments and such experiments were commissioned by Sirius Minerals from four established organisations; Texas A&M University, Durham University, University of Florida and Shandong Agricultural University. The contractual arrangements between Sirius Minerals and each University in relation to the type of experiment, glasshouse or field, soil type to be used, crops to be grown and treatments to be tested are not known. However, I consider that in many cases the type of experiment and treatments tested do not show that polyhalite has any special properties as a fertilizer.

**5.2.** General comments about the principles of doing experiments on the nutrient requirement of agricultural crops grown commercially under field conditions, for more details see the Appendix to this report.

***5.2.1.*** *Greenhouse and field experiments.* Research workers involved in crop and soil studies generally accept that the results on plant growth and yield seen in greenhouse experiments are often a guide to, but are rarely directly repeated in field experiments. In the greenhouse, water, temperature (and light) can be controlled but not in the field, unless water for irrigation is available. In pots in the greenhouse soil structure is optimised so that roots rapidly grow throughout the volume of soil in the pot, and when fertilizers are tested they are uniformly mixed throughout the soil in the pot so that the rapidly-growing root system has the greatest opportunity for the roots to find the added nutrients. In the field, soil structure is very variable and annual crops rarely exploit more than 25% of the top soil so there is less chance of them finding newly added nutrients especially potash and phosphate that essentially remain where they are placed in soil. (This is the reason why in RB209 the recommendation is to maintain soils with an adequate level of plant available phosphate, Index 2, and potash Index 2- for arable crops See Appendix A2 for more details). So the results of greenhouse experiments are treated with caution and only as a guide to what might happen in the field. Other than the experiments done at Texas A&M, all the results given in the ADAS report were obtained in greenhouse pot experiments and should be treated with great caution in relation to the possible effects of polyhalite under field conditions.

***5.2.2.*** *The basic principle in the conduct of experiments on plant nutrition.* Plants require different amounts of many nutrients and for each nutrient the amount required varies during growth. Thus, when doing experiments on the nutrient requirement of crops, whether in pots or in the field, it is essential to ensure that all plants have equal access to all nutrients other than that being tested. For example, if testing two forms of potash fertilizer it is essential that all pots in the greenhouse or plots in the field receive the same amounts of nitrogen and phosphate and if required, magnesium, sulphur and micronutrients. This essential need for a "level playing field" does not appear to have been followed in some of the experiments done at the four Universities and this has concerned the authors of the ADAS Report as noted in Section 3 of this report.

**5.3.** ADAS Report Section. 4.1 *Published literature.* This brief introduction is mainly a summary of the work by Barbarick and Barbarick's summary of work published by four other authors. (Barbarick is one of the four members of the Science Panel that Sirius Minerals commissioned to review the ADAS Report) This review of earlier work on polyhalite appears to have been concerned with using polyhalite as a source of potassium because it is noted that, in general polyhalite increased the growth of a number of plant species and was at least as effective as potassium chloride or potassium sulphate, and the ADAS Report basically treats polyhalite as a potash fertilizer. However, in discussing the earlier work, the ADAS Report notes that in most cases the nutrients in the treatments tested were not fully balanced so any additional responses to polyhalite in these experiments could be attributed to sulphur or magnesium. This is the principle concern with the conduct of the experiments, commissioned by Sirius Minerals and discussed in the ADAS Report, in most cases the nutrients applied in polyhalite were not applied also with the potash fertilizers tested.

**5.4.** ADAS Report Section 4.2 *Sirius Minerals Research* I have been allowed visual access only to the "Data Room" which contains the results of the 24 experiments that were made available to ADAS to produce their Report. The aim was to see whether I would have reached the same conclusions based on the data submitted by the four organisations which made the experiments. Given the poor level and lack of consistency in reporting the data, I have sympathy with the authors of the ADAS Report in making their summary. For example, data are sometimes given as dry weight or fresh weight, sometimes as aerial, sometimes as tops, sometimes as roots, sometimes as total, sometimes as biomass. For this reason in Table 9 of the ADAS Report the authors use the word biomass when not discussing yield. Frequently the yields in the “Data Room” do not give the units of measurement and although differences between treatments are being compared having the unit of measurement gives some indication of how well the experiment was done. In some cases the results in a pot experiment are presented as tonnes per hectare or bushels per acre of saleable produce, e.g. seed, grain and potato tubers. I assume that this has been done to present the yields in a way that a grower can more easily appreciate in relation to what might be achieved in the field. However, I consider such a conversion, done by multiplying a pot yield by some conversion factor, is very wrong when the yield of one or a few plants per pot grown under optimum conditions in the greenhouse is presented as “saleable yield” because this may greatly overstate the level of yield that might be expected in the field.

**5.5.** ADAS Report Section 4.2.1. *Methodology* Table 7 summarises the important characteristics of the soils used in the experiments. Some of the Texas data in terms of crops, years and pot or field experiment does not seem to agree with later information. The latter suggests that there were only two field experiments, those on potatoes and field peppers, all the other crops were grown in pots. To me the choice of soils for these experiments is very odd based on my personal experience of doing experiments testing different fertilizers over more than 40 years. When testing polyhalite I would have chosen soils with less than optimum levels of plant-available potassium and magnesium but adequate phosphorus and a pH above 6.0. Table 7 shows that, in general, soil pH appears satisfactory but available phosphorus is very low in the soils used in the Florida experiments and this may have restricted the response to potassium. By UK standards, plant-available soil K was very high in soils used in the experiments at Shandong and Texas A&M, and I would not expect to see a response to potassium, but I wonder whether these soils were included to show a response to sulphur applied in polyhalite. If so, this is a very poor choice because with a very limited number of experiments the effects of the two most important nutrients should be tested in all experiments. I’m surprised that Durham University did not characterise the Woburn soil, which suggests a lack of rigour in their approach.

**5.6**. ADAS Report Section 4.2.2.*Results.* This section of the ADAS Report is divided into two sub-sections. The first is titled “Polyhalite properties” and this is a statement of facts and there is nothing in this sub-section with which I would disagree. The second sub-section is “Crop response” and in discussing this sub-section I consider the information given in Tables

9, 10 and 11 separately. For many of the pot experiments the yield of roots is given and this can be done for pot-grown crops where all the roots are contained in the pot and root and growing medium can be fairly easily separated although many of the fine roots are usually lost during washing out. The authors of the ADAS Report appear to have used this data on roots in two ways. First in Table 10 they give the response of above and below ground part of the crop to the treatments tested. To give both improves the "appearance" of the data because it increases the number of times that there is a "large percentage of greater or equal response". However, tops cannot exist without roots and roots without tops so why show both separately? Second, recognising the issues involved in measuring root weights, above and below ground plant weights have been added together to give what the authors have called biomass and they have then used this data in subsequent tables. At a more fundamental level root weights in pot experiments have little practical value in relation to and for comparison with what happens in the field because root weights of field-grown crops are rarely determined, to do so is notoriously difficult.

**5.6.1**. ADAS Report Table 9 simply presents the response to polyhalite compared to **NO** potash fertilizer addition in the 23 experiments listed in Table 9. However, yields for 24 experiments are given in the "Data Room", apparently one experiment on oilseed rape at Durham has been omitted from Table 9. The authors of the ADAS Report make an important point in the earlier part of their report, which is not repeated here, when discussing these results. Namely, where polyhalite was compared with other straight fertilizers supplying potassium all the pots/plots received nitrogen and potassium but it is not clear whether the sulphur, calcium and magnesium supplied by polyhalite were balanced by equal amounts of these three nutrients given to the pots/plots testing other sources of potassium. As there is no comment that this was done, I assume that the treatments were not balanced so that if polyhalite gave a larger yield than the other straight potassium fertilizers the effect could well have been due to either sulphur, magnesium or calcium added in the polyhalite. In the experiments comparing fertilizer blends that included polyhalite (with some MOP to achieve the right amount of potassium) there was no control of soil plus nitrogen plus phosphorus to check whether there was any effect of potassium, and I assume that the commercial blends were not balanced with sulphur, magnesium and calcium. The data in Table 9 are presented in alphabetical order by crop and show that there is no systematic difference between crops in their response to potassium. It would have been surprising if the table had shown a systematic difference because all the evidence shows that crops respond to potassium in a similar way.

For each crop, Table 9 presents the number of trials made by each organisation but there is no information on the size and complexity of each experiment. For biomass and crop yield Table 9 also gives whether there was no response or a positive response to potassium or whether a response was not determined (ND); for example, yield was not determined in most of the experiments at Durham. Table 9 gives no indication of the size of the response where there was one. The summary in the last line of Table 9 notes that of the 23 experiments in the Table whole crop biomass was measured in only 16 and of these 16 only in 9 was there a positive response to potassium. Crop yield was measured in only 15 of the experiments and only in 10 of these was there a response to potassium. This lack of response to potassium poses two issues, which relate to poor experimental design and not adhering to appropriate protocols when doing experiments with crops (see Appendix A4). First, choice of soils; that there was a response to potassium in only about half the experiments suggests that perhaps the wrong soils were used, i.e. the soils used were already well supplied with plant-available potassium and no response to potassium would have been expected. Second, choice of treatments; although the soils used in the Texas experiments were particularly well supplied with plant-available potassium there was a response to polyhalite in all but one of the seven experiments they made. This suggests that the check treatments did not have equivalent amounts of sulphur and magnesium to those in the polyhalite and the "positive response to potassium" was in effect a response to sulphur and/or magnesium and not to some special/unique effect of polyhalite. These concerns do throw doubt on the validity of the results from a poorly designed experimental programme. As a note, my interpretation of the results in the "Data Room" for the Texas experiments suggests that there was a response by onions (no response in Table 9) and no response by sorghum (positive response in Table 9), however this does not alter the proportion of the soils which did respond to potassium.

**5.6.2**. ADAS Report Tables 10 and 11. These two tables attempt to summarise the responses to potassium applied in polyhalite and compare the responses with those of other sources of potassium applied in fertilizers that were included in the experiments. In relation to these two Tables, I have found it difficult to tell which experiments are included and I'm uncertain how, if at all, the results from the blended fertilizers tested in one experiment in Texas and Shandong and in two experiments in Florida have been included.  More importantly, I'm not convinced that the summaries should be presented as shown as discussed in the following paragraphs.

Table 10 gives data for both above- and below-ground plant growth, and Table 11 data for yield. The data as presented show that in a very large percentage of cases polyhalite gave an equal or greater response than the other potassium fertilizers but the proportion of cases where polyhalite was better than the other potash sources was much smaller. With respect to the authors of the ADAS Report I think these tables are confusing because although in the footnotes to the Tables they give the number of experiments in which a specific treatment was tested they give equal weight to the result regardless of the number of experiments in the Table. Additionally equal weight is given to all treatments although not all treatments were tested in all experiments.

Table 10 also gives the response of both the above and below (roots) part of the crop to the different forms of potash fertilizer tested. To be strictly fair these results can only be for the pot experiments where root weight was determined and I think this was done because I cannot always agree with the numbers of experiments for each treatment shown in the footnotes to Table 10. As noted previously I see no point in giving equal prominence to below ground (root) and above ground responses when the root weights have been measured in pot experiments, and especially in experiments where phosphate has been given as a basal dressing because roots respond more to phosphorus than to potassium. It would have been more appropriate to use total biomass in Table 10 because this was used in Table 9.

I find it difficult to understand why some treatments were chosen for testing, and in some cases they were only tested in one or two experiments, yet, as noted above, equal weight is given to the responses in Tables 10 and 11.

The treatment CPH is calcined (i.e. heat treated) polyhalite. Why heat polyhalite, which has a cost, when it is water-soluble and the nutrients it contains are plant available. I believe it was only tested at Durham in seven experiments and in all but two it gave a smaller above-ground yield than did polyhalite. I only know of one heat-treated material used in agriculture, calcined magnesite; heating the very hard magnesite mineral makes the magnesium more plant-available so that calcined magnesite is a cheaper form of magnesium than other magnesium fertilizers.

The treatment "Chem" was single salts mixed to supply an amount of potassium and sulphur, equilivent to that in polyhalite. It was tested only at Durham in the seven experiments that tested CPH; and as with CPH in all but two experiments it gave a smaller yield than did polyhalite. Where there was a larger yield with polyhalite this was probably because of the magnesium supplied with polyhalite and magnesium was not added in the “Chem” treatment.

The ADAS Report compares in Figure 13 the effects of CPH and “Chem” with those of polyhalite and shows that CPH decreased yields more than did “Chem”. As noted above it is difficult to understand why these treatments were included in the experiment and why they have been shown in Figure 13.

The treatment SOP-M (sulphate of potash magnesia, $2MgSO_4.K_2SO_4$) was perhaps included because unlike polyhalite it did not supply calcium and it could therefore be a control for any effect of calcium in polyhalite. It was tested in four experiments at Durham and two experiments in Florida. It gave slightly smaller yields than polyhalite in four of these experiments.

In the ADAS Report and much of the information provided by York Potash, polyhalite is considered as a source of potassium. Consequently, the principal comparison for polyhalite must be with muriate of potash (MOP), if there is an issue with the chloride in MOP, and with sulphate of potash (SOP), if there is a crop response to sulphur, which is added in polyhalite. Polyhalite and both MOP and SOP were included in 19 of the 24 experiments, the five where the comparison was not made were at Durham. I attempted to make my summary of the yields given by these three fertilizers, using data from the “Data Room”. Since doing this a spread sheet with all the information in the “Data Room” has been made available, which includes the actual yields in each experiment. As the yields were not presented in the ADAS Report it would be unfair to present and discuss them in this part of my review, which specifically deals only with the ADAS Report. Consequently this spread sheet is presented in an Addendum to this review and the yields are discussed there.

Section 4 of the ADAS Report does not present or discuss yields given by the commercial fertilizer blends which were compared with blends that included polyhalite, as a source of potassium. However, Section 6 of the ADAS Report includes comments on the possible use of fertilizer blends containing polyhalite but even there it does not discuss the yields of the blended fertilizers that were tested on behalf of Sirius Minerals. The yields given by these blended fertilizers are presented and discussed in the Addendum to this review. However, I will refer to the ADAS Report discussion on using polyhalite in fertilizer blends in Section 7 of this review later.

Frequently the ADAS Report notes that polyhalite could be used for crops with a large requirement for sulphur, such as oilseed rape (rape seed) and onions. Using UK DEFRA recommendations for these two crops I have calculated in Table 1 the shortfall in potash when using polyhalite and this would have to be made good by applying muriate of potash. I repeat a point made before, even where growers know that sulphur is required I believe they would prefer to apply all the potash as muriate of potash and use another readily available source of sulphur, especially when a large proportion of the amount of potassium required has to be applied as muriate of potash.

Table 1 Additional potash required when polyhalite used to supply the sulphur required by oilseed rape and onions

| | Recommended rate* | | Amount of polyhalite | Amount applied in polyhalite | | Shortfall |
|---|---|---|---|---|---|---|
| | $K_2O$ | $SO_3$ | for $SO_3$ | $SO_3$ | $K_2O$ | in $K_2O$ |
| Crop | kg/ha | kg/ha | kg/ha | kg/ha | kg/ha | kg/ha |
| Rapeseed | 70 | 75 | 156 | 75 | 22 | 48 |
| Onions | 225 | 50 | 104 | 50 | 15 | 210 |

* Potash recommendation for soils at ADAS K Index 1

**5.6.3.** Summary to Section 4 in the ADAS Report

Two points are made in the summary to Section 4 of the ADAS Report:

- In around 90% of experiments with a range of crop species, **Polyhalite always produced an equal or greater growth response** compared with other wider used potash fertilisers (when balanced for potash supply).
- **Polyhalite produced an equal or greater growth response** to sulphate of potash in 8 of 9 experiments (when balanced for potash supply).

These two bullet points make the point that the yield effects were noted “when balanced for potash supply” and, by implication, they were not balanced for sulphur and magnesium in particular. This is noted in many other parts of the ADAS Report, often the statement being that only the potash supply was balanced. Thus, a “level playing field” was not created by applying similar amounts of sulphur, magnesium and calcium with the other potash fertilizers as was applied with the polyhalite. So the apparent benefit from using polyhalite could simply be due to some combination of the sulphur, magnesium and calcium and not to some unique property of the polyhalite.

The most serious aspect of Tables 9, 10 and 11 is that the yield effects of polyhalite are classified as being equal to or better than those of other potash fertilizers, like muriate of potash. Thus, the most important information required by growers, namely the yields grown and the size of the increases in yield are not available to the grower. I consider this most unusual, especially as the absolute yields could be given in an Appendix similar to those showing the results of the fertilizer spreading trials. Possibly as a result of this comment a spread sheet including the yields in each experiment has been made available and is given in the Addendum to this review.

## 6. Comments on Section 5 of the ADAS Report - Polyhalite as a Multi - Nutrient Fertilizer

Considerable effort must have gone into compiling the data in this Section of the ADAS Report. The data, taken from reliable sources, has focussed on demonstrating the amount of potassium that is in the 16 most-widely grown crops globally. My concern would be with some of the inferences made. In Section 5.2 "Global Crop Production" it is noted that "nutrient offtake provides the most appropriate guide to fertilizer requirement". This statement is not correct because, and especially for potassium, many crops contain much more nutrient at the most active periods of growth than is removed in the crop at harvest. For example, for winter wheat and spring barley the amount of potassium in the crop at harvest is only about 60% of the potassium in the crop at the time of maximum dry matter production. To ensure that there is sufficient plant-available nutrient in soil to meet the maximum needs of the crop, the most appropriate method is to ensure that soil is maintained at the critical level of plant-available potassium appropriate to the soil type and cropping pattern, and replace the potassium removed in the harvested crop as discussed in the Appendix to this report. This critical level will allow for the amount of potassium released by weathering of soil minerals each year. In those soils where a large proportion of the potassium in the crop has come from such sources the requirement for additional potassium inputs of fertilizer each year is small.

Although the ADAS Report notes that the total global nutrient offtake is approximately 31.41 Mt $K_2O$ annually no attempt is made, rightly in my view, to relate this amount to the production from existing mines, and therefore the need for new ones.

Mention is made in Section 5.3.2 about the salt tolerance and chloride sensitivity of crops, and the ADAS Report attempts to show that polyhalite has a role to play in mitigating their effects. However, Table 17 in the ADAS Report shows for the 16 global crops discussed in the Report that salt tolerance has not been determined for two and of the remaining 14 only potatoes are known to be partially tolerant/sensitive to salt concentration. This does not suggest that there would be a large market for polyhalite in relation to growing crops sensitive to salt. Also, in many cases the sensitivity of crops to salt is related to other soil conditions, principally moisture level, and this is not affected by using polyhalite. The chloride issue is often mentioned but increasing quantities of muriate of potash have been used for the last 150 years to provide potassium essential for achieving good yields of most crops. If there was an issue with chloride it would not be used globally on the scale that it is today, and where there is an issue with a few crops the problem is well-known and sulphate of potash can be used.

Section 5.3.4 – Best fit crops The report uses the estimated nutrient offtakes of potassium, sulphur and magnesium for each of the 16 global production crops to assess whether each had a high, medium or low demand (on a three tier scale) for these three nutrients. Using this criterion, the Report then attempts to see where the demand by the crops would be best matched using polyhalite. Table 18 looks impressive but I'm not sure what value it has. It would appear to follow an earlier attempt by York Potash to demonstrate that the ratio of the three nutrients in polyhalite matches the concentration in crops. Earlier in this report it is shown that there is no relationship between the ratio of the three elements in crops and in polyhalite, not least because the ratio of $K_2O$ to $SO_3$ in polyhalite is very different to the ratio of potassium to sulphur in plants.

## 7. Comments on Section 6 of the ADAS Report - Polyhalite use in Agriculture

This Section in the ADAS Report notes that polyhalite would be a useful component of blended fertilizers because *"generally it would not be appropriate to use straight polyhalite to supply all the potassium requirements because of the excess amount of sulphur applied"*.

Also throughout this report there is little evidence that polyhalite has any unique property that would make it a useful straight fertilizer compared to other potash sources even for crops with a large requirement for sulphur.

The use of fertilizer blends compared to using straight fertilizers is discussed in the Appendix to this report. In Section 6.1 of the ADAS Report fertilizer strategies for UK crops are discussed briefly compared to the fuller discussion in the Appendix to this report. The latter focuses on using fertilizers to supplement the existing supply of each plant-available nutrient in soil and to do this a blend of individual fertilizers each supplying the required amount of each nutrient can be a very successful method of meeting the nutrient requirements of the crop being grown.

Tables 20, 21 and 22 give nitrogen, phosphate, potash and sulphur recommendations for winter wheat, oilseed rape and first cut grass silage given in RB209 together with examples of polyhalite blends with nitrogen and phosphorus fertilizers, which at an appropriate rate per hectare would supply approximately the recommended amount of the four nutrients. (Note RB209 frequently recommends that the total nitrogen requirement is applied in more than one application. Thus, the total recommended nitrogen is not applied in the fertilizer blend.) In all five examples the composition of the blend and the amount applied has been adjusted to supply just the required amount of sulphur in polyhalite. Thus, the footnotes to each table say that the blend included muriate of potash to supply the required amount of potash. (Note, my calculation suggests that for the second example in Table 21, polyhalite would supply all the small amount of potash required.) For the examples in Tables 20 and 22 the polyhalite supplies only 12 kg $K_2O$ so that a large proportion of the potash would be supplied by muriate of potash. I reiterate my belief that it would be better to make NPK blends from muriate of potash and another source of sulphur where it is needed rather than use a combination of polyhalite and muriate of potash.

The ADAS Report does not give yields given by the fertilizer blends tested in the pot experiments commissioned by Sirius Minerals. These are now given and discussed in the Addendum to this review.

## 8. Summary

The North York Moors National Park Authority have received a report, The Agronomic Case for Polyhalite by ADAS, 8 April 2014 (The ADAS Report) as part of the submission by York Potash in their Planning Application to extract polyhalite from underground deposits using access via works in the National Park. At the request of The National Park Authority, I have reviewed the case made in this Report for the use of polyhalite as a fertilizer based on my experience as a research scientist specialising in soil fertility and crop nutrition. I also had access to some of the data from the field and pot experiments discussed in the ADAS Report that are lodged in the "Data Room", but are not generally available, so that I could see whether my interpretation of the data agreed with that of the authors of the ADAS Report,

Polyhalite is a naturally-occurring mineral that contains four nutrients, potassium, magnesium, calcium and sulphur required for growth by plants. York Potash maintains that it could be used as a fertilizer to supply these four nutrients to crops in the field. However, most of the case presented in the ADAS Report emphasises the use of polyhalite as a fertilizer supplying potassium, i.e. as a potash fertilizer. Agronomically, polyhalite has no special properties that make it uniquely suitable for use as a potash fertilizer in particular, or any other type of fertilizer for a number of reasons.

- As a potash fertilizer polyhalite supplies too little potassium (only 14% $K_2O$) compared to other readily available potash fertilizers like muriate of potash (MOP, 60% $K_2O$) and sulphate of potash (SOP, 50% $K_2O$). Consequently, to apply the same amount of potash to a field a very much larger amount of polyhalite has to be added compared to MOP. See Appendix A7.
- The ratio of the four elements in polyhalite is not the ratio required by plants growing in the field, polyhalite contains too much sulphur relative to potassium, and not all the four nutrients may be required at the same time if there is sufficient in plant-available forms in the soil. See Appendix A5.
- It is suggested that polyhalite could be used to supply sulphur for those crops which require large amounts of sulphur like oilseed rape and onions. But these crops have a large requirement for potassium also and if polyhalite is used an additional source of potassium has to be added.
- It is suggested that polyhalite could be used as a component of a blend of different fertilizers, a "blend or blended fertilizer", each component supplying one or more

plant nutrients, so that the number of nutrients and the amount supplied meets the need of the crop. In all the examples of blended fertilizers given in the ADAS Report, polyhalite supplies too little potassium and MOP is used to bring the potassium content to the required level. If MOP has to be used why not use all MOP. See Appendix A7.

- Using polyhalite as a straight fertilizer or as a component of a blend must rest on well-proven evidence that it offers benefits, in terms of growth and crop yield, over and above those given by the simple fertilizer materials supplying the same four nutrients either as straight fertilizers or as components of a blend. Such evidence is not provided by the experiments that tested polyhalite as a fertilizer, experiments that were commissioned by Sirius Minerals PLC, and discussed in the ADAS Report, Most experiments were pot experiments and it is generally accepted by scientists working in crop nutrition that the results from pot experiments in the controlled conditions in the greenhouse are rarely applicable to what might happen under field conditions. Therefore, the results of the experiments use by York Potash should be treated with great caution.
- The case for using polyhalite in the ADAS Report rests on the results of a total of only 22 experiments and the evidence provided by these experiments is reviewed in Section 4 of the ADAS Report. Section 4 of the ADAS Report notes that, "Conclusions from the research funded by Sirius Minerals were in agreement with the findings of Barbarick (1991) who showed that the potash supply from Polyhalite was at least as effective as that from MOP (muriate of potash) and SOP (sulphate of potash). Then, very importantly the Report notes: *"some caution should be taken in interpreting these results because although the potash content of the fertilizer applications (i.e. those tested in these experiments) was usually equilivent for each fertilizer added, the fertilizers almost always differed in the content of other nutrients (required by plants for optimum growth) including sulphur, magnesium and calcium and these were not accounted for or balanced in any of the studies reported. Therefore, the differences observed may not necessarily be the result of greater potash availability for plants, but instead may be related to the availability of one or more of the other nutrients."* The implication of this comment is that the yield advantage to be gained by using polyhalite rather than muriate of potash or sulphate of potash either singly or in blended fertilizers is not substantiated because the design

of the experiments which tested these materials was flawed in that like was not compared with like.

- The final paragraph to the Executive Summary of the ADAS Report (page ii) simply notes: "In summary, polyhalite is a valuable source of major plant-available nutrients (i.e. *potash, sulphur and magnesium) that can be used to produce multi-nutrient fertiliser products or as a straight product. ….*" This is not a sufficiently strong endorsement for using polyhalite as a fertilizer because the plant nutrients in polyhalite are readily available world-wide in other materials; potassium as potassium chloride (muriate of potash, MOP), sulphur as gypsum/phosphogypsum, magnesium as kieserite/calcined magnesite or magnesian limestone and calcium as chalk and limestone, and polyhalite has no unique properties in this respect.
- To review the technical and agronomic content of the ADAS Report, Sirius Minerals established a Science Panel to the ADAS Report. The members of the panel signed off the following, "*…we are satisfied that this report (*the ADAS Report*) is a valid and reasonable summary of existing knowledge and relevant information. We agree with the principal conclusion that polyhalite is an effective source of potassium, magnesium calcium and sulphur for crop nutrition. We further agree that markets for these nutrients exist currently worldwide in agriculture and horticulture and that they are expected to grow as world food demand increases."*. Interestingly, the comments of the Science Panel, like those in the ADAS Report, do not mention any unique properties of polyhalite in its ability to supply the four plant nutrients, potassium, magnesium, calcium and sulphur that would make polyhalite different from the many other fertilizers that supply these four nutrients. In my opinion, the phraseology used, as in the example above, is very neutral and does not provide an overwhelming endorsement for the use of polyhalite as an essential replacement for other fertilizers supplying these four nutrients It is very important to remember that the information presented in the ADAS Report is based on only 24 experiments, most of which were pot experiments in the controlled environment of the greenhouse and it is generally accepted that the results of such experiments are rarely confirmed when the same treatments are tested in the harsher conditions when crops are grown in open fields. My interpretation of the results of the experiments discussed in the ADAS Report is that there is no evidence that polyhalite has any unique properties that justify its use as a straight fertilizer or as a component of a blended fertilizer

compared to the use of other readily-available fertilizers supplying the same nutrients in the same amount.

A. E. Johnston

December 2014

This Appendix accompanies the Review of an ADAS Report 'The Agronomic Case for Polyhalite', dated 8 April 2014.

The review and this appendix were written by Mr A. E. Johnston, Lawes Trust Senior Fellow, Rothamsted Research, Harpenden, at the request of the North York Moors National Park Authority. This appendix is intended to supply additional background information to observations and comments made in the review.

## Contents

## A1. Fertilizers

Fertilizers are mostly inorganic salts as opposed to organic manures and composts, which by definition contain organic material of complex chemical composition. Fertilizers are often considered to fall into one of three groups, straights, compounds or blends. A straight fertilizer is one which contains a single compound although it may contain more than one plant nutrient. For example, ammonium sulphate is a single chemical compound but it does contain two plant nutrients, nitrogen as ammonium and sulphur as sulphate. Likewise, potassium sulphate contains both potassium and sulphur. However, in most cases more than one compound may be needed to provide the nutrients required and the fertilizer industry has developed techniques for combining the compounds required and producing a granular fertilizer in which the nutrients required are in the correct proportion in each granule. Blended fertilizers are a physical mixture of two or more compounds, each of which contains one or more of the nutrients required. Each compound maintains its physical identity, and they are blended to give the chemical composition required for a particular field.

Most farmers will try to use a compound or blended fertiliser to supply the nutrients required by the crop they are growing on each field so that the fertiliser is applied as quickly as possible with the least number of passes by the fertiliser spreader. If soil analysis shows that a field is below the critical level in potash or phosphate then a farmer may decide to apply either muriate of potash or triple superphosphate as appropriate to remedy the deficiency. Most soils contain sufficient plant-available calcium and the level is maintained by ensuring that the acidity (pH) of a soil is near neutral (pH about 6.5 for arable crops, pH 6 for grassland) by applying calcitic or magnesian limestone (according to availability) or chalk when required. If soil acidity is controlled by additions of magnesian limestone then this maintains the magnesium level otherwise deficiency when it occurs can be corrected by a foliar spray. Sulphur is usually only applied where deficiency is known or thought to occur.

### *A1.1. Polyhalite as a fertilizer*

There is nothing wrong with polyhalite in the sense that it is not poisonous. It is a naturally-occurring mineral containing three of the six major plant nutrients, namely potassium, calcium and magnesium but the concentration of each of these three nutrients is too small for polyhalite to be a good source of each individually, especially if the farmer’s need is to only supply one of the three. Also, each of these three nutrients is present as its sulphate salt, potassium sulphate, calcium sulphate and magnesium sulphate. Consequently, although sulphur is a plant nutrient and is taken up by plant roots as sulphate, the amount of sulphate applied in polyhalite, especially when used to apply sufficient potassium, is far in excess of the sulphate requirement of an annual crop. Thus there is an issue about how polyhalite is marketed, as a potash, magnesium, sulphur or calcium fertilizer. Much of the published material from York Potash, and especially the ADAS Report considers polyhalite to be a potash fertilizer.

## A2. Fertilizer Recommendations

After WWII, the Government established the National Agricultural Advisory Service (NAAS), which became the Agricultural Development and Advisory Service (ADAS), to provide free and impartial advice to farmers including recommendations for the amounts of nitrogen, phosphate and potash, to apply to crops. Farmers could then compare these recommendations with those given by commercial organisations selling fertilisers and then make their own decisions as to the amount of fertiliser to use. These recommendations, updated as appropriate, are published in RB209 the first edition was in 1971. Once ADAS became an Agency selling its services, Rothamsted Research was asked to take the lead in preparing the 8$^{th}$ edition published in 2010 to maintain the impartiality of the advice.

Current fertiliser recommendations in the UK and many countries are based on the premise that plant nutrients can be applied in fertilisers and organic manures but the amounts used should supplement the amount of each nutrient already in soil in a plant-available form, which is invariably very much less than the total amount in soil. Although there are some differences in the total number of elements, often about 22, found in plants, the mineral elements present in the largest amounts are nitrogen (N), phosphorus (phosphate, P), potassium (potash, K) sulphur (S) magnesium (Mg) and calcium (Ca). Plant roots take up these nutrients from the soil solution (the water in the soil) but not as elements but as ions. For example, nitrogen as nitrate ($NO_3^-$), potassium as $K^+$, sulphur as $SO_4^{2-}$, magnesium as $Mg^{2+}$, and phosphorus as $H_2PO_4^-$. While these ions must be in the soil solution for uptake by roots, all but two can be retained in soil in plant-available forms. The two which are not retained in soil are nitrate and sulphate and because they are in the soil solution they can be removed from soil whenever rainwater drains through the soil. Thus, RB209 the fertiliser recommendations published by DEFRA for England, Wales and Northern Ireland (RB209 is not used in Scotland) differentiates between nitrogen and sulphur and the other nutrients.

*A2.1. Recommendations for potassium, magnesium and calcium*

For potassium and magnesium that are retained in soil in plant-available forms, RB209 takes two complimentary approaches to maintaining the required amount in soil and thus the fertility and productive capacity of soils. First, a soil should be raised to and then maintained at a critical, plant-available level of each nutrient, which has been determined in field experiments, and is set so that farmers should be able to optimise yields and maximise efficiency of use by other agronomic inputs in most years while maintaining the fertility of their soil. The critical level is maintained by replacing the amount of each nutrient removed each year in the crop taken from the field. For potassium the critical level given in RB209 is K Index 2- for arable crops and grass, and K Index 2+ for vegetables. The maintenance application can be calculated for each field using the known amount of crop removed and the percentage potash in the crop using the table of potash concentrations for many crops given in RB209. The second of the complimentary approaches is to take a representative soil sample from each field every 3 to 5 years and have it analysed for plant-available potassium to ensure that the critical level is being maintained by the amounts of potash added since the last soil sample was taken. If the measured level is declining below the critical level more potash should be added, if the measured level has greatly increased less potash can be applied.

RB209 does not give recommendations for calcium mainly because many soils in England, Wales and Northern Ireland are naturally neutral ($pH_{water}$ about 7) or contain free calcium carbonate, i.e. they contain large amounts of plant-available calcium, or the pH can be raised to 7 by applying readily-available ground chalk or limestone.

*A2.2. Recommendation for sulphur and nitrogen*

There is an increasing risk of sulphur deficiency in crops grown in the UK principally because aerial inputs of sulphur from industrial emissions to the atmosphere are declining, and fertilisers like ammonium sulphate and single superphosphate (which contains calcium sulphate) are now used less frequently. Thus, where deficiency is recognised it may become necessary to apply sulphur to those crops that have a large demand.

Soil analysis for plant-available sulphur is not a good indicator of sulphur availability because sulphate is very soluble and is readily leached from soil. Consequently, RB209 has no Table of S Index values similar to those of phosphorus, potassium and magnesium. Leaf analysis for sulphur is a more reliable guide to possible deficiency but the result may be too late to correct deficiency in the current year but will serve as a guide to possible future need to apply sulphur. The British Survey of Fertiliser Practice shows that only about 42% of arable crops and 6% of grassland receives any form of sulphur. This is a reflection of farmers responding to situations where sulphur deficiency would be likely to decrease yields. Where there is a risk of loss of yield due to sulphur deficiency RB209 gives a general recommendation for cereals (25-50 kg $SO_3$/ha) and for oilseed rape (50-75 kg $SO_3$/ha).

Recommendations for nitrogen are based on analysing a soil sample (usually to 90cm) to determine nitrate and ammonium (mineral nitrogen) or on a knowledge of previous cropping and the possible amount of mineral nitrogen that will become available to the crop during the growing season.

## A3. Behaviour of potassium in soil and current potash use

### *A3.1. Behaviour of potassium in soil*

The FERA Report commissioned by York Potash makes the (obvious) point that if potassium is removed from soil the total amount of potassium will decline eventually to a level at which crop yields are jeopardised. The FERA Report gives no estimate of how long it might take to get to such a very low level in soil because there is too little appropriate data. What data exist are for some heavy textured soils and they suggest that it may take many decades of potassium removal to get to such a low level.

Soil potassium can be thought of as existing in three pools: (i) K that is readily available for uptake by plant roots, exchangeable K; (ii) K that is not immediately available but can become plant available comparatively easily, non-exchangeable K; and, (iii) K that is in soil minerals that can become available over long periods, mineral K; exchangeable K is usually a very small proportion of the total K in soil. Exchangeable K is measured by routine soil analysis and is the best estimate of immediately plant available K. As exchangeable K is removed by root uptake it is replaced by K from the non-exchangeable pool and, consequently exchangeable K will decline more slowly than the removal of K in crops would suggest. Thus, many farmers who have their soils analysed regularly often see a very small decline in exchangeable K as K is removed and until the critical level is reached they (correctly in my view) see no reason to apply potash fertiliser. Unless the removal of K is related to the change in plant-available potassium (exchangeable K) there is a risk of over-emphasising the importance of the decrease in potash inputs in fertiliser relative to the amounts removed in harvested crops. Eventually the exchangeable and non-exchangeable K will be depleted and crop yields begin to decline and farmers respond by applying K. To me it is not credible to suggest that any farmer will risk not achieving the yields required to ensure the farm remains financially viable for lack of an application of potash, which is readily available at prices that can be afforded. If plant-available potash in soil declines to very low levels then it is possible but very expensive to remedy this situation.

*A3.2.Current potash use*

Maintaining soil fertility is crucial to the ability to produce food now and in the future. For nutrients like potassium and magnesium that are retained in soil it is essential to maintain a soil at the appropriate critical level for the soil and farming system. An important aspect of this is to relate changes in plant-available K in soil to the potassium balance (K applied *minus* K removed). This can be done at a field and farm level for the benefit of the farmer or it can be done at a regional or national level, and at this level the data has been used in both the FERA Report and by York Potash. The K balance for England and Wales can be estimated using data on potash applications in fertiliser from the British Survey of Fertiliser Practice (BSFP) and data on potash removal using data on average crop yields (from DEFRA statistics) and percent K in crops in tables in RB209. Using this data, Mr C J Dawson (Consultant) has prepared a K balance for cereals, potatoes, oilseeds and sugar beet each year since 1974. Initially the K balance was positive but since the early 1980s the annual K balance has been negative, i.e. less potash is being applied annually in fertiliser than is removed in crops, and this data has been widely used in the FERA Report and by York Potash (I also have used it as have many others). However, in the last few years BSFP has been collecting data on inputs of potassium in organic manures to these arable crops and I understand from Mr Dawson that his preliminary assessment is that the amount of potash added in organic manures may be three times as large as that added in fertilisers. Additionally, the increasing trend to apply green waste compost to arable land is also adding potash. Recently one farmer told me that green waste compost had added 250 kg $K_2O$/ha, another had added 140 kg $K_2O$/ha. The opportunity to recalculate the potash balance and include the potash in organic manures could mean that overall there is a positive rather than negative K balance.

This change in the estimate of the K balance may explain an apparent discrepancy between the previous K balance data and changes in the plant-available potassium in the "national soil"; i.e. with a negative K balance the amount of plant-available K in soil should decrease. Until recently in England and Wales there was a Representative Soil Sampling Scheme (RSSS) which was an adjunct to the Survey of Fertiliser Practice. On a subset of farms visited each year to ask about fertiliser use, soil samples were taken. From the early 1970s to the late 1990s the proportion of soils in each of the K Index groups 0 to 5 changed little, i.e. there was no appreciable change in plant-available K. Although the RSSS has been discontinued an estimate of the proportion of soils in each group is available in data from the Professional Agricultural Analysis Group (PAAG). Their report in 2010 shows little change in the proportion of soils in each K Index group from the RSSS data. The apparent anomaly that plant-available K in soil was not declining appreciably with an estimated negative K balance can now be satisfactorily explained when the K balance is adjusted to include the potassium added to arable soils in organic manures and composts. While there are soils in K Index 0 and 1 the proportion does not seem to be increasing. Soils in K Index 0 and 1 are probably very sandy soils where it is difficult to increase the plant-available potash or where the farmer sees no need to increase the K Index.

## A4. Greenhouse and field experiments

### *A4.1. Limitations to the results of pot experiments in the greenhouse*

Research workers involved in crop and soil studies generally accept that the results on plant growth and yield seen in greenhouse experiments where plants are grown in small pots of soil are often only a guide to, but are rarely directly repeated in field experiments. In the greenhouse, water, temperature (and light) can be controlled but not in the field, unless irrigation is available to supply water. In pots soil structure is optimised and when fertilizers are tested they are uniformly mixed throughout the soil in the pot. Consequently, the root system grows rapidly throughout the soil volume and there is the greatest opportunity for the roots to find the added nutrients. (For root growth think of what you see when you remove a plant from a pot bought from a garden centre compared to the roots when you dig up a plant in the garden.) In the field soil structure is very variably and annual crops rarely exploit more than 25% of the top soil so there is less chance of them finding newly added nutrients especially potash and phosphate that essentially remain where they are placed in soil. So the results of greenhouse experiments are treated with caution and only as a guide to what might happen in the field. Most of the crop trials commissioned by Sirius Minerals and discussed in the ADAS Report, were conducted in pots in the greenhouse and the results should be considered as only a guide to the possible effects of the fertilizers when tested under field conditions, and the results should be treated with considerable caution.

### *A4.2. Basic principles for conducting pot and field experiments*

The basic principle in the conduct of experiments on plant nutrition is to ensure that all plants have equal access to all nutrients other than that being tested. For example, if testing two forms of phosphate fertilizer, in pots or in the field, it is essential that all pots in the greenhouse or plots in the field receive the same amounts of nitrogen, potash and if required, magnesium, sulphur and micronutrients. Nearly all the experiments undertaken for Sirius Minerals compare polyhalite and muriate of potash as sources of potassium and ignore the essential need for a "level playing field". Although nitrogen and phosphate may have been added to all pots or occasionally plots, equivalent amounts of sulphur, magnesium and calcium to those in polyhalite have not been added to the pots/plots treated with muriate of potash. Under these conditions, if the yields with polyhalite are larger than those with muriate of potash the increase in yield would most likely be due to the sulphur and/or magnesium added in the polyhalite.

## A5. Balanced fertilisation and balanced supply

Documents from York Potash frequently use the phrases "balanced fertilisation" and "balanced supply", and it is important that the current definitions and application of these phrases are understood so that they are used correctly.

### *A5.1. Balanced fertilisation*

The comments by York Potash regarding the use of polyhalite and "balanced" fertilisation indicate a total misunderstanding about the concept of "balanced fertilisation". Balanced fertilisation, the buzz phrase of the last 30 or so years, came into use when large amounts of nitrogen fertiliser were being applied to soils in many developing countries together with little or no potash and phosphate. The lack of phosphate and potash additions together with the small inherent content of these two nutrients in the soil limited the response to nitrogen, and a policy of advising that the use of nitrogen fertilisers should be "balanced" with applications of phosphate and potash was developed. Today the concept of balanced fertilisation can be defined more rigorously. Soil usually contains some but variable amounts of most of the nutrients required by plants in forms that are readily-available for uptake by roots. To meet the total nutrient requirements of a crop the balance (i.e. the amount required *minus* that already in soil) should be applied as fertiliser (or organic manure) hence "balanced fertilisation". In practice this means that a farmer may need to apply some potassium or magnesium but rarely both nutrients which is the case when polyhalite is used. Polyhalite will never be a "balanced fertilizer" because it contains no nitrogen and phosphorus

*A5.2. Balanced supply*

York Potash frequently use the phrase "balanced supply", personally I think that the word "ratio" better describes what is being discussed because it is the ratio of the four elements in crops and polyhalite in relation to both supply and requirement. So I will use ratio rather than balanced supply. In various statements on their website, York Potash contends that polyhalite provides the four plant nutrients, potassium, sulphur, magnesium and calcium, in the same ratio that these four nutrients are found in plants. To show this relationship York Potash makes a rather unusual calculation. First, %S, %$K_2O$, %CaO and %MgO are added together and then for each of the four elements its percentage is expressed as a percentage of the sum, which simply produces a ratio. This has been done for both polyhalite and a range of crop species. First there is a fundamental error. By convention the concentration of each element in a plant is expressed in terms of the element, *not the oxide* in plant dry matter so using the percent of the oxide for potassium, calcium and magnesium is wrong. However, I have redone the calculation using %S, %K, %Ca and %Mg for three major crop species, wheat, rice and maize, and for polyhalite. The results in Table A show that compared to the average ratio of S: K: Ca: Mg in these three crops, polyhalite provides 6 times more sulphur, 3 times too little potassium, 2.6 times too much calcium and only for magnesium about the right amount . I contend that redoing the calculation for the other crops mentioned by York Potash will produce very similar ratios, and the results clearly do not support the contention that polyhalite provides a balanced supply (or ratio) of these four nutrients in relation to the concentration in the crop.

Table A Proportion of sulphur (S), potassium (K), magnesium (Mg) and calcium (Ca) in the sum of the percentages of these three elements in three major crops and polyhalite

| Crop | Proportion of | | | |
|---|---|---|---|---|
| | Sulphur | Potassium | Magnesium | Calcium |
| Wheat | 9 | 76 | 5 | 10 |
| Rice | 4 | 81 | 6 | 9 |
| Maize | 8 | 68 | 14 | 10 |
| mean | 7 | 75 | 8 | 10 |
| Polyhalite | 41 | 25 | 8 | 26 |

As noted elsewhere, the primary aim of using fertilizers is to supplement the supply of plant-available nutrients in soil not by applying a fertilizer which contains a given ratio of plant nutrients, some of which may not be required when sufficient already exist in soil. While the amount of each element in plant-available forms in the soil is important there is no relation between this amount in soil and the concentration in crops. Table B shows the plant-available concentrations of potassium, magnesium and calcium in two different soils and the percentage potassium, magnesium and calcium in a 10 tonne per hectare crop of grass grown on these two soils. For magnesium the concentration in soil and the percentage in crop was least and the ratio of potassium and calcium in both soil and crop relative to magnesium set as 1 is also shown.

Table B Plant-available potassium K), magnesium (Mg) and calcium (Ca) in soil and percentage of the three elements in 10 t/ha grass and in parenthesis the ratio relative to magnesium (Mg) as 1

| | Plant-available concentration in soil,mg/kg and *(ratio)* | | | Percent in grass dry matter % and *(ratio)* | | |
|---|---|---|---|---|---|---|
| | K | Mg | Ca | K | Mg | Ca |
| Soil 1 | 244 *(6)* | 42 *(1)* | 3290 *(78)* | 3.5 *(32)* | 0.11 *(1)* | 0.6 *(5)* |
| Soil 2 | 158 *(1)* | 156 *(1)* | 1300 *(8)* | 3.3 *(17)* | 0.19 *(1)* | 0.5 *(3)* |

In both soils there was very much more plant-available calcium than potassium yet there was about 6 times more potassium in the crop than calcium. Current research suggests that plants exert some degree of control over the amount of each element taken up by the roots, and the essential need to achieve optimum yields is ensuring that there is sufficient plant-available nutrient in soil. The latter can be achieved in various ways and the least satisfactory is to use a fertilizer with a fixed composition.

## A6. The neutral status of polyhalite

The neutral status of polyhalite is not a unique property of this mineral. Like all inorganic fertilisers polyhalite is neutral because the total positive charge on some ions is balanced by the total negative charge on other ions. For example, muriate of potash is equal parts of potassium $K^+$ and chloride $Cl^-$ so the positive charge on the potassium ion is balanced by the negative charge on the chloride ion.

The issue with polyhalite is that it contains a large amount of sulphate ($SO_4^{2-}$) and, as noted above, the sulphate ion is not retained in soil and when rainfall causes water to drain through the soil the very soluble sulphate ion is removed in the drainage. To maintain the electrical neutrality of the drainage a positive ion has to accompany the sulphate. In many cases this positive ion is calcium, $Ca^{2+}$, but it could be $Mg^{2+}$ or $H^+$. When much of the sulphate in polyhalite is not taken up by a crop the sulphate will eventually leach out and most probably take with it the magnesium and calcium added in the polyhalite. Thus, the cost of purchasing magnesium and calcium in polyhalite will have no benefit to the farmer.

## A7. Polyhalite as a potassium fertiliser

### *A7.1. Supply and demand*

In my view it is unlikely that polyhalite would succeed as a potash fertiliser in a world that is awash with potash deposits. The United States Geological Service (acknowledged as a world authority on mineral resources) estimates that 34 million tonnes (Mt) $K_2O$ was mined in 2012 from an active reserve of 9500 Mt, an annual extraction rate of 0.36% of this reserve. In addition they estimate total world resources of about 250 billion tonnes. The world is not short of reserves of potash. York Potash has asserted that the Cleveland Potash mine at Boulby could not meet the total domestic requirement even at the current rate of use by farmers. Current statistics suggest that we export more potash than we import. If there was a large increase in domestic requirement there are sources in Germany and Russia and further afield in Canada. To me it is inconceivable that the major suppliers of fertilisers in the UK, who operate internationally, could not source sufficient potash on the world markets to meet UK requirements.

*A7.2. Polyhalite as a straight fertilizer*

A straight fertilizer is one which contains a single compound although it may contain more than one plant nutrient. Polyhalite contains four plant nutrients and as polyhalite is soluble in water this is not an issue with using polyhalite as a source of potassium, magnesium, calcium and sulphate. The major problem with polyhalite is the small percentage of potassium, 14% $K_2O$, and large percentage of sulphur, 48% $SO_3$, and this unbalanced composition leads to two major problems.

First, most crops take up more potassium than any other nutrient and thus a much larger amount of polyhalite would be required to supply the required amount of compared to muriate of potash. Table C shows the amount of potassium, sulphur, magnesium and calcium in a 50 t/ha crop of potatoes and a 3 t/ha crop of soybean and the mounts of sulphur, magnesium and calcium that would be added if polyhalite was used to supply all the potassium required. Polyhalite would add 13 times more sulphur, 5 times more magnesium and 24 times more calcium.

Table C Amounts of potassium, sulphur, magnesium and calcium in 50t/ha potatoes and and 3t/ha soybean and the amounts of sulphur, calcium and magnesium added when polyhalite is used to supply the amount of potasium required

| | Amount element, kg/ha, in crop | | | |
|---|---|---|---|---|
| Crop | Potassium (K) | Sulphur (S) | Magnesium (Mg) | Calcium (Ca) |
| Potatoes, 50 t/ha | 166 | 20 | 9 | 7 |
| Soybean, 3 t/ha | 50 | 6 | 7 | 8 |
| Amount of polyhalite if sole source of K | Amount element in amount of polyhalite required to supply K | | | |
| 14.3 t/ha for potatoes | 166 | 272 | 51 | 172 |
| 4.3 t/ha for soybean | 50 | 82 | 15 | 52 |

Second, compared to using muriate of potash, a much larger amount of polyhalite would be required to supply the recommended application of potassium for most crops. This, in turn, means that the spreading operation would have to be stopped to refill the hopper many more times when using polyhalite than when using muriate of potash. Table C gives the area covered by one fill of a 1 tonne capacity hopper when applying the recommended amount of potash as either polyhalite or muriate of potash for both winter wheat and potatoes.

Table D Comparison of the area covered using polyhalite and muriate of potash to supply the same amount of $K_2O$ to potatoes and winter wheat

| Potash source | Potash requirement for | Area covered per fill of a 1 tonne capacity spreader |
|---|---|---|
| | 8 t/ha winter wheat, straw baled | |
| Muriate of potash, 60% $K_2O$ | 85 kg $K_2O$/ha requires 142 kg MOP | 7.04 hectares |
| Polyhalite, 14% $K_2O$ | 85 kg $K_2O$/ha requires 608 kg polyhalite | 1.65 hectares |
| | 50 t/ha potatoes | |
| Muriate of potash, 60% $K_2O$ | 300 kg $K_2O$/ha requires 500 kg MOP | 2.00 hectares |
| Polyhalite, 14%$K_2O$ | 300 kg $K_2O$/ha requires 2143 kg polyhalite | 0.46 hectares |

The smaller area covered for each fill of the spreader when using polyhalite will considerably lengthen the time required to spread a give quantity of polyhalite. I think this would make polyhalite as a straight fertilizer unattractive to most farmers.

*A7.3. Polyhalite as a constituent of an NPK fertiliser blend*

There are issues around using polyhalite as a straight fertilizer because of its small concentration of potassium and large concentration of sulphur. Consequently, it has been suggested that it could be a component of a fertilizer blend, i.e. a fertilizer containing a number of different compounds each one supplying one or more plant nutrients. In their presentation of the Current Crop Study Results, June 2013, York Potash gives many examples of using polyhalite as a constituent of an NPK blend fertilizer. Invariably the sulphur content is given as %S while the fertiliser recommendations require percent sulphur as %$SO_3$. Blend No. 1 contains 5.5% N and 69% polyhalite containing 33% $SO_3$. To apply even a modest application of 100 kg N/ha using this product would added about 600 kg/ha of $SO_3$, an amount far in excess of the sulphur requirement of the crop and at an unnecessary cost to the farmer. Blends 2, 3, 4 and 6 with a higher NPK analysis than Blend 1 all require use of muriate of potash. Will Blenders want to hold stocks of two products when muriate of potash will meet all the potash needs required in the blend?

This Addendum accompanies the Review, by A.E. Johnston, of an ADAS Report ‘The Agronomic Case for Polyhalite’, dated 8 April 2014.

In the ADAS Report and much of the information provided by York Potash, polyhalite is considered mainly as a source of potassium. Consequently, the principal comparison for polyhalite must be with muriate of potash (MOP), if there is an issue with the chloride in MOP, and with sulphate of potash (SOP), if there is a crop response to sulphur, which is added in polyhalite but not in MOP. Polyhalite and both MOP and SOP were included in 19 of the 24 experiments discussed in the ADAS Report, the five experiments in which this comparison was not made were Durham. My principle concern with the ADAS Report was that the information in Tables 10 and 11 simply presented the effects of polyhalite as equal to or better than the other fertilizers tested which supplied potassium. As polyhalite will only be used as a fertilizer this information is of little use to growers and farmers for whom two aspects about the yields are of importance. First, the yields at which polyhalite was equal to that of other potash fertilizers makes it possible to decide, on the basis of cost, whether or not to use polyhalite and in doing so apply other nutrients which may not be needed by the growing crop, and whether extra potash fertilizer must be bought to make good a deficiency in potassium when using polyhalite. Second, if polyhalite yields more than other potash fertilizers how large was the difference and what was the reason for the difference? A spread sheet with all the information from the experiments discussed in the ADAS Report has now been made available. This table is given here as Addendum Table A.

Most of the experiments were in the controlled conditions in the glasshouse, only those on onions and potatoes at Texas are specifically identified as field experiments while the other experiments at Texas on onions, sorghum and soybean were I suspect pot experiments and the yields have been calculated on a hectare or acre basis using some arbitrary factor. The results are presented in a variety of ways, just as g (grams, presumably per pot), as g/pot, as g/plant, as tonnes per hectare (t/ha) and as bushels per acre (bu/ha). While I have considerable reservations about whether the magnitude of the effects and the effects themselves which were measured in pot experiments would be the same under field conditions, the fact that the treatments were compared under identical conditions makes it possible to make comparisons based on the results that are reported.

Full details of the experiments discussed in the ADAS report are presented in Addendum Table A below. I have summarised what I believe to be the information most relevant to a comparison of the yields given by polyhalite, muriate of potash (MOP) and sulphate of potash (SOP) in Table 1 using only data from the 19 experiments in which all three fertilizers were compared. Other treatments may have been included in these and other experiments to test some other factor but these are not relevant to the comparison of the three important potassium sources. I have only used the data most relevant to a grower, namely the yield of the saleable part of the plant where this was given or the above-ground part of the plant as this could relate more directly to the saleable produce. I have not included the yield on the control plot because all three potash fertilizers increased plant growth of a wide range of crop species when compared to the yield on the control/check plot, except when the soil used on the control plot contained adequate potassium. Polyhalite would not be expected to decrease yield compared to that given on the control treatment. I have not used the yield of roots, sometimes given as below ground yield, which is reported in some experiments. As noted in my review, this can only be done for pot experiments in the greenhouse, they have little relation to root growth of crops in the field, and the result is of little interest to growers, they don’t harvest and sell the roots of winter wheat or of maize.

Table 1 Yields of the crops in experiments in which polyhalite (PH) was compared with muriate of potash (MOP) and sulphate of potash (SOP).

| Crop part, nitrogen applied, kg N/ha | | Unit of measurement | Yield | | |
|---|---|---|---|---|---|
| | | | PH | MOP | SOP |
| Glasshouse experiments | | | | | |
| Durham | | | | | |
| | Cotton 2 aerial | DW[a], g | 0.58 | 0.60 | 0.64 |
| | Oilseed rape, aerial | FW[a], g | 23.4 | 21.1 | 24.3 |
| | Soybean aerial | DW[a], g | 1.12 | 1.13 | 1.06 |
| | Wheat 2 aerial | DW[a], g | o.490 | 0.261 | 0.471 |
| | Wheat 3 aerial | DW[a], g | 0.228 | 0.243 | 0.239 |
| | Potatoes tubers | FW[a], g | 79.5 | 57.1 | 78.1 |
| Florida | | | | | |
| | Corn, ears | DW[a], g | 59.2 | 43.9 | 64.6 |
| | Sugar cane, total yield | DW[a], g | 20.86 | 24.36 | 24.36 |
| Shandong | | | | | |
| | Peanuts, seed | g per plant | 6.59 | 6.16 | 6.26 |
| Texas | | | | | |
| 50 N | Pepper, fruit | g per pot | 141.1 | 141.0 | 162.8 |
| 100 N | Pepper, fruit | g per pot | 187.6 | 197.7 | 207.4 |
| 150 N | Pepper, fruit | g per pot | 181.4 | 178.5 | 196.2 |
| Field experiments | | | | | |
| Texas | | | | | |
| 50 N | Pepper, fruit | t/ha | 15.03 | 14.95 | 15.23 |
| 150 N | Pepper, fruit | t/ha | 15.68 | 15.71 | 16.11 |
| 56 N | Potatoes, tubers | t/ha | 22.91 | 22.02 | 23.35 |
| 168 N | Potatoes, tubers | t/ha | 26.68 | 25.61 | 25.77 |
| Other experiments[b] | | | | | |
| Texas | | | | | |
| 56 N | Onions, total yield | t/ha | 88.09 | 86.43 | 90.15 |
| 168 N | Onions, total yield | t/ha | 92.69 | 91.82 | 92.23 |
| 50 N | Sorgham, grain | t/ha | 6.51 | 6.55 | 6.70 |
| 150 N | Sorgham, grain | t/ha | 7.05 | 7.01 | 7.20 |
| | Soybean, grain | bu/ac | 34.12 | 34.12 | 34.19 |

[a] DW and FW dry weight and fresh weight, respectively

[b] It is not clear whether these were glasshouse or field experiments, probably glasshoue experiments but the yield converted to t/ha or bu/ac

When presented accurately and simply as in this Table it is clear that polyhalite gave appreciably the same yield as MOP or SOP in all the comparisons. Where MOP gave a smaller yield than polyhalite it was SOP that gave the same yield presumably because there was a deficiency of sulphur which was made good by the sulphur in polyhalite and SOP. Where nitrogen was tested it increased the yield in some cases, as might be expected, but the relationship between the yields given by the three fertilizers was not affected.

Blends of NPK fertilizers in which some of the potassium was supplied as polyhalite were compared with two commercially available blends in a total of four experiments which as far as it is possible to tell were in pot experiments in the controlled environment of the greenhouse. There were two experiments in Florida, Corn Study 2 and Sugarcane Study 2 and one experiment each in Shandong (corn) and Texas (soybean). The yields are also given in Addendum Table A, which includes the yields for six crop components for the Florida Corn Study 2. Four of these crop components are not included in Table 2, which gives the data in a more readily understandable way.

Table 2 Yields of the crops in experiments in which blends of fertilizers were tested

| Experiment and crop part | Unit | Check | Polyhalite blends | | | Commercial blends | | |
|---|---|---|---|---|---|---|---|---|
| Florida | | | Poly 12 | Poly 16/14 | *mean* | NPK 12 | NPK 16/17 | mean |
| Corn study 2, total DW | g/plant | 3.0 | 62.6 | 71.7 | 67.2 | 69.3 | 67.9 | *68.6* |
| total grains | g | 25.6 | 31.8 | 34.1 | *33.0* | 27.7 | 22.0 | *24.8* |
| Sugar cane 2 Yield | kg/ha | 3.02 | 29.98 | 26.99 | 27.48 | 27.17 | 28.43 | 27.8 |
| Texas | | | | | | | | |
| Soybean 2, grain | bu/ac | 30.06 | 33.63 | 33.98 | *33.8* | 33.59 | 34.43 | *34.01* |
| Shandong | | | | | | | | |
| Corn cob weight | g/plant | 0.8 | 18.7 | 8.0 | *13.4* | 15.6 | 10.2 | *12.9* |

The check/control yields in the two experiments in Florida and in that at Shandong are very much smaller than those given by the fertilizer blends, a 20-fold difference in some cases. Table 2 shows that in all but one case the yields with the two blends were similar and they have been averaged and shown in Table 2 in italics. Comparing these mean yields shows that there was little difference between the commercial blends and those containing polyhalite except for the grain yields in the corn experiment in Florida, although there was not the same difference in the mean total yield. As the commercial blend was unlikely to contain sulphur this difference in grain yield might have been an effect of the sulphur in polyhalite on grain production. Even if there was no added sulphur and magnesium with the NPK blend there was no benefit on total yield where the polyhalite blend was used, and if sulphur was required it could have been added with the commercial blend. The two blends containing polyhalite would have to contain MOP and as noted in the review as the amount of nutrients in the blend increased, the proportion of MOP would have to increase. In the 12:12:12 blend some 40% of the potassium would be supplied by MOP and this proportion would increase to nearly 80% in the 16:16:16 blend. As mentioned earlier in the review and in the Appendix would a company supplying blended fertilizers necessarily stock both polyhalite and MOP to make blends, this is especially so when the blends contain a large amount of MOP to supply the required amount of potassium.

The statement that polyhalite produces an equal or greater growth response compared to other widely used potash fertilizers should be treated with great caution on the basis of the data in Table 1 above. There is no evidence that polyhalite does other than supply four plant nutrients, potassium, sulphur, magnesium and calcium, of which the most important are potassium and sulphur. A major issue with polyhalite is that the ratio of these four nutrients in polyhalite is not the ratio found in plants or required by plants, there is far too much sulphur relative to potassium. It is unrealistic to expect growers to buy and apply nutrients not required by the crop they wish to grow. All four plant nutrients are widely available in a number of fertilizers so that the amount of each applied to soil can be adjusted to supplement the readily plant-available supply in the soil and so meet the requirement of the crop being grown.

## Addendum Table A: Overview Tables from York Potash Data Room – shown overleaf

| | | | | | | 1 control | 2 Control Soil plus back ground nitrogen and phosphate at the same addition level as the treatments | A synthetic replication of the nutrients with polyhalite. BALANCED | Polyhalite | Calcined polyhalite | BALANCED FOR K PLUS an S SUPPLY | BALANCED FOR K SUPPLY ONLY | BALANCED FOR K PLUS an S and Mg SUPPLY | Is PH significnatly worse than the control? | Block | Control | Control.K Product | Control.K Rate | Control.Product.Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | GENSTAT table mean outputs | | | | | | | | | ANOVA statistical significance of difference | | | | |
| Discussion Notes | Table 1 inclusion | | Data Room entry | | units | Soil alone | Soil + N +P | Chem | PH | CPH | SOP | MOP | SOPM | | Key | P<0.05 | P0.05-0.1 | P>0.1 | |
| 1 | N | Variate: Cotton_Aerial_DW | Du Cotton 1 output | | g | 1.333 | 1.983 | 2.29 | 1.742 | 1.826 | | | | N | | 0.293 | 0.036 | 0.217 | 0.11 |
| 2 | Y | Variate: Cotton_Aerial_DW | Du Cotton 2 output | | g | 0.52 | 0.48 | 0.606 | 0.582 | 0.787 | 0.642 | 0.598 | | N | | 0.493 | <.001 | <.001 | 0.009 |
| 3 | Y | Variate: OSR_Aerial_FW_30days | Du OSR 1 output | | g | 5.39 | 14.3 | | 23.37 | | 24.28 | 21.09 | 19.71 | N | | <.001 | <.001 | 0.051 | 0.012 |
| 4 | N | Variate: Belinda_Seed_FW | Du OSR 2 output | | g | 0.52 | 3.14 | 2.65 | 3.93 | 2.57 | | | | N | | 0.011 | 0.006 | 0.389 | 0.506 |
| 5 | Y | Variate: Potato_tuber_FW | Du potato output | | g | 76 | 72.9 | | 79.5 | | 78.1 | 57.1 | 87.4 | N | | 0.982 | 0.003 | 0.077 | 0.069 |
| 6 | Y | Variate: Soya_Aerial_DW | Du Soybean output | | g | 0.947 | 1.117 | | 1.117 | | 1.057 | 1.129 | 1.035 | N | | 0.481 | 0.425 | 0.003 | 0.06 |
| 7 | N | Variate: Soya_RootDM | Du Soybean output | | g | 0.873 | 0.733 | | 1.142 | | 0.836 | 1.203 | 0.841 | N | | 0.076 | <.001 | 0.002 | <.001 |
| 8 | N | Variate: Cordiale_Aerial_DW | Du Wheat 1 output | | g | | 0.07 | 0.195 | 0.2238 | 0.1856 | | | | N | | <.001 | 0.033 | 0.019 | <.001 |
| 9 | Y | Variate: Cordiale_Aerial_DW | Du Wheat 2 output | | g | 0.1267 | 0.3033 | 0.3267 | 0.49 | 0.405 | 0.4717 | 0.2611 | | N | | <.001 | <.001 | <.001 | <.001 |
| 10 | Y | Variate: Cordiale_Aerial_DW | Du Wheat 3 output | | g | 0.07 | 0.3133 | | 0.2275 | | 0.2392 | 0.2431 | 0.2769 | N | | <.001 | 0.03 | 0.008 | <.001 |
| 11 | N | Variate: gallant_aerial_DM | Du Wheat 4 output | | g | | 0.05 | 0.165 | 0.2256 | 0.1522 | | | | N | | <.001 | <.001 | 0.043 | 0.012 |
| 12 | N | Variate: Grafton_Aerial_DW | Du Wheat 5 output | | g | | 0.0933 | 0.1478 | 0.155 | 0.145 | | | | N | | 0.069 | 0.828 | 0.896 | 0.057 |
| | | | | | | | | | | Blend | | | | | | | | | |
| 13 | Y | Variate: Ear_corn_dry_weight_g | Florida Corn Study 1 | | g | | 13.2 | | 59.2 | | 64.6 | 43.9 | 51.6 | N | 0.789 | <.001 | 0.013 | 0.224 | 0.143 |
| 14 | Y | Variate: Yield | Florida Sugarcane study 1 | | g | | 20.08 | | 20.86 | | 24.36 | 24.36 | 18.21 | N | | 0.605 | 0.042 | 0.169 | 0.831 |
| 15 | N | Variate: ROOTW | Shandong peanut output | | g/plant | | 0.867 | | 0.724 | | 0.739 | 0.844 | 0.838 | N | | 0.456 | 0.232 | 0.081 | 0.238 |
| 16 | N | Variate: SEEDW | Shandong peanut output | | g/plant | | 6.87 | | 6.59 | | 6.26 | 6.16 | 6.95 | N | | 0.748 | 0.756 | 0.682 | 0.794 |
| 17 | N | Variate: SHOOTW | Shandong peanut output | | g/plant | | 11.3 | | 9.73 | | 11.12 | 11.65 | 10.4 | N | | 0.699 | 0.274 | 0.565 | 0.359 |
| 18 | Y | Variate: Fruit_Yield_Mg_ha | Texas Field Pepper output | 50N | Mg/ha | | 14.01 | | 15.03 | 15.25 | 15.23 | 14.95 | | N | | 0.045 | 0.648 | 0.026 | 0.998 |
| 19 | N | Variate: Fruit_Yield_Mg_ha | Texas Field Pepper output | 150N | Mg/ha | | 14.79 | | 15.68 | 16.13 | 16.11 | 15.71 | | N | | 0.045 | 0.648 | 0.026 | 0.998 |
| 20 | Y | Variate: TuberYield_T_ha | Texas Field Potato output | 56N C | t/ha | | 17.35 | | 22.906 | 21.898 | 23.349 | 22.022 | | N | | <.001 | <.001 | <.001 | <.001 |
| 21 | N | Variate: TuberYield_T_ha | Texas Field Potato output | 168N C | t/ha | | 18.497 | | 26.679 | 26.102 | 25.768 | 25.607 | | N | | <.001 | <.001 | <.001 | <.001 |
| 22 | Y | Variate: Fruit_Yield_g_pot | Texas Glasshouse pepper output | 50N | g/pot | | 108.3 | | 141.1 | 171.1 | 162.8 | 141 | | N | | <.001 | <.001 | <.001 | 0.838 |
| 23 | N | Variate: Fruit_Yield_g_pot | Texas Glasshouse pepper output | 100N | g/pot | | 125.4 | | 187.6 | 218.4 | 207.4 | 197.7 | | N | | <.001 | <.001 | <.001 | 0.838 |
| 24 | N | Variate: Fruit_Yield_g_pot | Texas Glasshouse pepper output | 150N | g/pot | | 132.8 | | 181.4 | 210.9 | 196.2 | 178.5 | | N | | <.001 | <.001 | <.001 | 0.838 |
| 25 | Y | Variate: Total_yield | Texas Onion output | 56N C | t/ha | | 77.55 | | 88.09 | 89.34 | 90.15 | 86.43 | | N | 0.385 | <.001 | 0.334 | 0.102 | 0.991 |
| 26 | Y | Variate: Total_yield | Texas Onion output | 168N C | t/ha | | 79.94 | | 92.69 | 92.41 | 92.23 | 91.82 | | N | 0.385 | <.001 | 0.334 | 0.102 | 0.991 |
| 27 | Y | Variate: Grain_YIELD_T_ha | Texas Sorghum output | 50N | t/ha | | 6.071 | | 6.509 | 6.903 | 6.699 | 6.545 | | N | 0.799 | 0.042 | 0.361 | 0.023 | 0.997 |
| 28 | N | Variate: Grain_YIELD_T_ha | Texas Sorghum output | 150N | t/ha | | 6.43 | | 7.047 | 7.317 | 7.204 | 7.013 | | N | 0.799 | 0.042 | 0.361 | 0.023 | 0.997 |
| 29 | Y | Variate: Grain_Yield_bu_ac | Texas Soybean 1 output | | bu/ac | | 31.07 | | 34.12 | | 34.19 | 34.12 | | N | 0.019 | <.001 | 0.981 | <.001 | 0.61 |

| | | | | | | | NPK12 | NPK16 | | | | Is PH significnatly worse than the control? | Block | Control | Control.K Product | Control.K Rate | Control.Product.Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | ANOVA statistical significance of difference | | | | |
| Discussion Notes | Table 2 inclusion | | Data Room entry | Unit | Soil alone | Soil + N +P | Commercial 12 | Commercial 16/1 | Poly12 | Poly16 | Poly14 | | Key | P<0.05 | P0.05-0.1 | P>0.1 | |
| 30 | N | Variate: Ear_corn_dry_weight_g | Florida Corn Study 2 | g/plant | 1.1 | | 49.4 | 49.5 | 49.2 | 52.7 | | N | 0.308 | <.001 | 0.919 | <.001 | 0.781 |
| 31 | N | Variate: Root_dry_weight_g | Florida Corn Study 2 | g/plant | 1.41 | | 20.35 | 22.54 | 19.2 | 23.99 | | N | 0.114 | <.001 | 0.125 | <.001 | 0.223 |
| 32 | N | Variate: Tops_dry_weight_g | Florida Corn Study 2 | g/plant | 1.6 | | 48.9 | 45.3 | 43.4 | 47.7 | | N | 0.282 | <.001 | 0.604 | <.001 | 0.822 |
| 33 | Y | Variate: Total_plant_dry_weight_g | Florida Corn Study 2 | g/plant | 3 | | 69.3 | 67.9 | 62.6 | 71.7 | | N | 0.177 | <.001 | 0.516 | <.001 | 0.753 |
| 34 | N | Variate: Estimated_yield_MT_Ha | Florida Corn Study 2 | t/ha | 1.967 | | 2.126 | 1.687 | 2.442 | 2.618 | | N | 0.23 | 0.55 | 0.012 | <.001 | <.001 |
| 35 | Y | Variate: Total_grains_weight_g | Florida Corn Study 2 | g | 25.6 | | 27.7 | 22 | 31.8 | 34.1 | | N | 0.23 | 0.55 | 0.012 | <.001 | <.001 |
| 36 | Y | Variate: Yield | Florida Sugarcane study 2 | Hg/ha | 3.02 | | 27.17 | 28.43 | 29.98 | 26.99 | | N | | <.001 | 0.634 | <.001 | 0.962 |
| 37 | Y | Variate: COBW | Shandong corn output | g/plant | 0.8 | | 15.6 | 10.2 | 18.7 | | 8 | N | | 0.015 | 0.009 | 0.013 | 0.964 |
| 38 | Y | Variate: Grain_Yield_bu_ac | Texas Soybean 2 output | bu/ac | 30.06 | | 33.52 | 34.43 | 33.63 | | 33.98 | N | 0.595 | <.001 | 0.291 | <.001 | 0.985 |